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A New Boundary Treatment for Analyzing Dynamic Structure-Medium Interaction

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A new and comprehensive non-reflecting boundary treatment has been developed for use in numerical analyses of structure-medium interaction. The method relies only on Newton's laws of motion and on the general mathematical identities which apply to all wave propagation phenomena. It therefore applies for all materials regardless of their constitutive behavior and for arbitrary geometric changes (finite deformation). The method has been implemented in a number of codes and is being successfully used for several different classes of analysis.

The verification of the method requires a series of computations. This paper described these numerical analyses and also provides a description of the fundamental equations underlying the new technique.

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bar	1.000 000 X E + 2	kilopascal (kPa)
degree Farenheit	$(t_{oF} - 32) / 1.8$	degrees Celsius
foot	3.048 000 X E - 1	meter (m)
foot-pound-force	1.355 818	joule (J)
inch	2.540 000 X E - 2	meter (m)
kip (1000 lbf)	4.448 222 X E + 3	newton (N)
kip/inch^2 (ksi)	6.894 757 X E + 3	kilopascal (kPa)
kips per foot	14.5932	kilonewtons per meter
kips per sq. ft. (ksf)	4.788 X E + 3	pascal (Pa)
ksi	6.894 757 X E + 6	pascal (Pa)
pound	0.4536	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E - 1	newton-meter (N·m)
pound-force/inch	1.751 268 X E + 2	newton/meter (N/m)
pound-force/foot^2	4.788 026 X E - 2	kilopascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilopascal (kPa)
pressure (psi)	6.894 757 X E + 3	pascal (Pa)
square inch	6.452 X E - 4	meter^2 (m^2)
square foot	9.290 X E - 2	meter^2 (m^2)
slug	1.459 390 X E + 1	kilogram (kg)

TABLE OF CONTENTS

FIGURES

SECTION 1

INTRODUCTION

The analysis and prediction of the dynamic response of structures is an important technical area for the Defense Nuclear Agency. In many cases, in particular when significant loading arises from ground or water shock wave propagation, the details of the structural loading depend upon the response of the structure itself. This is in contrast to classical structural analysis, in which the loading is specified and is independent of the details of the structure or its response.

The feedback mechanisms which make the loading on a partially or totally submerged or embedded structure depend on its response are significant when the mechanical characteristics, such as inertia, stiffness, wave speeds, impedance, etc., of both the structure and the field medium are of comparable magnitude. This is often the case when the free-field environment involves mechanical wave propagation in either water or geological materials. Feedback mechanisms of this kind are collectively termed structure-medium interaction (SMI), and any well-founded analysis of structural response to ground or water shock must take SMI into account.

Because modern structural analysis is characterized by large three-dimensional computations, it is difficult to marshal sufficient computer resources to include both the numerics of the detonation and wave propagation (often through large expanses of field media) and the structural analysis in one computation. Typically, the analysis is performed by analyzing the field environment without the structure present, and then using those results in turn to analyze the structural response by means of a structure-medium analysis. This paper presents a new methodology with a greatly improved capability to deal effectively with SMI problems.

SECTION 2

PREVIOUS APPROACHES TO SMI

In order to examine possible approaches to SMI, it is useful to review the definition of the free-field environment. This is the response of the field medium without any structure present. In particular, the mechanical free-field environment is defined in terms of the stresses and motions which would be observed at locations corresponding to a structure if the structure weren't there. Because of the presence of the structure, and as a result of waves scattered from it, the actual environment is different from the free-field. The waves scattered by the structure radiate into the field medium, disturbing what would otherwise be the free-field environment, and altering the stresses and motions in the structure's neighborhood.

The use of numerical (finite difference or finite element) techniques to determine the shock loading on a structure, and on the material adjacent to it, requires the analyst to model an essentially unbounded physical domain with a finite grid. The oldest and simplest, but least appropriate, method for dealing with SMI is to ignore it entirely. In this "null approach" the free-field stresses existing at the (absent) structural boundaries are used directly and without modification as the loads on the structure. Simple conditions, e.g. fixed, free or roller, at fictitious boundaries placed sufficiently far from the area of interest allow determination of the solution in the region of interest up to the time of first arrival of the reflected waves from the boundary; thereafter the solution is perturbed by the presence of the artificial boundaries. This approach is costly in terms of computer resources, but furnishes useful data for short duration response. Of course, the results of such analyses are inadequate for longer term response.

An improvement on the null approach is the Plane Wave Approximation [1], which is the simplest non-trivial SMI procedure. In this approach the scattered waves are characterized by the assumption that they are plane waves propagating normally outward from each point of the structure. It can be shown that this assumption becomes asymptotically correct for the high frequencies (short wavelength) components of the scattered signal. Such an approach may be adequate in cases for which the loading is

short-lived compared to the characteristic response time of the structure. Variants, such as the Curved Wave Approximation, are also sometimes employed, providing somewhat improved accuracy at high frequencies compared to the Plane Wave Approximation. Lower frequencies, however, are still not well characterized.

A related procedure is the "viscous" boundary condition of Lysmer and Kuhlemeyer [2]. This "transmitting" boundary is based on the behavior of outgoing one-dimensional body waves in an isotropic linearly elastic medium. For such waves the significant stress component σ is related to the corresponding component of particle velocity v by $\sigma = -\rho c v$, where c is the wave speed. (Note that for dilatational waves $c = c_P$ and σ and v are the stress and velocity components normal to the wave front; for shear waves, σ is a shear stress, v the corresponding velocity component tangential to the wave front, and the appropriate c is the wave speed for shear, c_S). In multidimensional elastic problems, the Lysmer-Kuhlemeyer condition is exact for normal incidence on a planar boundary. Fortunately, it works very well for near normal incidence as well. However, for larger angles of incidence, the technique loses accuracy.

The Lysmer-Kuhlemeyer boundary condition can also work reasonably well for inelastic materials, provided the appropriate "c" values are utilized. (Often, values of c_P and c_S based on the stiffer unloading behavior work tolerably well). Other approaches, e.g., [3,4], work only in the frequency domain and require that the material be elastic. One interesting paper is [5], which, although it deals with an elastic medium, contains a number of observations that could apply to the inelastic case as well. In that paper the problem is addressed in terms of various order approximations; the lowest order approximation is, in fact, that introduced by Lysmer and Kuhlemeyer.

The Doubly Asymptotic Approximation [6,7] (and its variants) represents an attempt to deal with the lower frequency (longer wavelength) components of the scattered signal. This is done by characterizing the asymptotic response of the field medium to scattered waves at vanishingly low frequencies, and interpolating between this and the high frequency approximation to obtain an approximate representation of the interaction over the entire range of frequencies. In the case of a fluid, the low frequency behavior entails a "virtual mass", while for a solid field medium a virtual "stiffness" is appropriate.

The Doubly Asymptotic Approximation is widely used and often gives acceptable results, particularly for linear problems in which effects at intermediate frequencies are secondary.

The null approach, the Plane Wave Approximation and the Doubly Asymptotic Approximation (and their variants) each usually involve the direct application of the interaction procedure to the surface of the structure. This circumvents the need to devote computer resources to the analysis of the field medium, but also limits the accuracy of the interaction analysis. In an attempt to capture in a more accurate way the response of the field medium, the soil-island, or structure-island procedure was introduced [8]. By using specified free-field input to drive a comprehensive model of a structure and the surrounding ground, the soil-island procedure provided a method for dealing with SMI in numerous cases of interest. The method was successfully applied to the relatively short time response of US and Soviet missile silos. Originally, the approach used kinematic boundary conditions (the free-field motions) to drive the island boundaries. Of course, these boundaries are arbitrary surfaces; they should be chosen "sufficiently far" away from the structure so that the motions on the boundaries are "minimally" affected by the scattered waves, yet sufficiently close to the structure so that the computational resources devoted to the calculation of the response of the near-field medium are kept as small as possible.

For calculations extending over long times, waves which reflect off the structure and impinge on the island boundary from within should be transmitted out (because the island boundary is not a real physical surface). If free field velocities (or tractions) are specified on the boundary, any waves arriving from within the island are reflected back inside, as from a rigid (or free) surface. These spurious reflections then contaminate the computed solution at the structure. It should be noted that, aside from the presence of the structure, spurious signals can arise from differences in the discretization and/or constitutive behavior in the island from those in the free-field.

For these reasons, some SMI analyses have combined the island approach with an interaction boundary [9,10,11]. In other words, the boundaries of the island are driven by a combination of the free-field traction and velocity. This combination is chosen to mimic an outwardly transmitting boundary (as far as internally scattered waves are concerned) by

means of an interaction scheme such as the Plane Wave or Doubly Asymptotic Approximation. Although such a method is not perfect, it can significantly enhance the accuracy of the analyses for longer times when the primary loading arises outside the island and any internally generated waves are not too strong. If one somehow "knew" the correct velocity (and/or traction), then applying the "known" field velocity (and/or traction) would be perfectly legitimate. Because the solution is not known until after the interaction problem is solved, one must view the procedure as one of successive approximations. This is the approach outlined in [9], and involves use of both the stress and velocity in combination to load the structure. In practice, although both tractions and velocities are needed and used on the boundary, only a particular combination corresponding to a generalization of. the condition of Lysmer and Kuhlemeyer is actually applied.

In spite of the fact that the procedure outlined in the preceding paragraph is often considerably more effective than its predecessors, there remain many situations for which the procedure is either impractical and/or inaccurate. This is especially true when the field medium is highly nonlinear and the response involves important effects over a broad range of frequencies (high, low and intermediate). In most of the cases in which it was applied, the approach worked as well as it did for several reasons. First, the soil materials for which the procedure was applied exhibit considerable hysteresis (damping). Secondly, the interaction solution near the structure had strong high-frequency, short wavelength, signals which attenuate quickly. The most important reason, however, was that only short duration results were of interest. Because only the very short-time response of the structure was needed, the immediate reflections of the SMI-induced waves back from the island boundaries were not strong enough to compromise the results.

Recently, new classes of problems have stretched the technique to its limits of applicability. Requirements to determine the long-time response of structures and systems, and to deal with the special problems in assessing conventional weapon effects, necessitated further development of the island technique. As a result, the advanced SMI method presented in this paper was developed. The new procedure is appropriate regardless of the constitutive behavior of the field medium, and represents the scattered

signals with good accuracy. The new approach has been implemented in a number of existing computer codes and meets the needs of some of the new classes of problems which confront the Defense Nuclear Agency.

SECTION 3

THE NEW PROCEDURE

The new structure-medium interaction procedure begins by decomposing the actual solution at an instant of time in the neighborhood of the structure (near-field) into a datum (usually the free-field) component which is known a priori and an additional scattered component arising from the fact that the actual SMI problem is different from the datum. This scattered part of the solution is defined simply as that obtained by subtracting the datum solution from the total (actual) solution. Because the datum solution is assumed to be known throughout time, so that the full (including interaction) solution can be constructed at a later time if the additional scattered part of the solution can be updated to that later time. This updating is clearly the only difficult part of the procedure; the methodology for performing it is outlined below.

A key observation concerning the additional scattered waves is that they propagate away from the structure into the field medium. More specifically, if a convex surface were chosen around the structure, say as an island with a small amount of field material, the additional scattered waves propagate through that surface only in an outward sense. Therefore, as far as this scattered part of the solution is concerned, such a surface appears as a "transmitting" boundary - allowing outward-propagating signals to pass through without reflection back into the island. This means that updating the scattered solution is equivalent to applying a transmitting boundary at such an island surface.

The scattered waves arriving at the artificial boundary are decomposed into normally and tangentially propagating parts by means of alternating direction and operator splitting techniques. (This is consistent with the local internal finite element procedure). Therefore, the local high-frequency effects are represented in an incrementally linear fashion (although there may be material and/or geometric nonlinearities), while the global, lower-frequency effects are determined automatically by the internal material properties and the geometry of the whole grid. The tangential components of the stress gradient (required for the equation of motion) near the boundary are computed using the available neighboring elements along the boundary surface. However the normal component of the

stress gradient cannot be computed because no element is available (such an element would be outside the grid, as shown in Figure 3-1). As shown below, Hadamard's compatibility identity for outgoing waves can be used to relate spatial to time derivatives in the equations for the evolution of the scattered solution; this allows the elimination of S, the unknown phase velocity of any wave arriving at the boundary.

As the island analysis proceeds, its results are continually compared to the boundary input (either free-field or datum). Differences in the velocity or traction between these are attributable to the arrival at the boundary of waves generated internally in the island. More precisely, the changes in the boundary nodal velocity are determined from three contributions:

(a) the change in the specified (datum or free-field) velocities,

(b) the change due to the normally propagating part of the internally generated arriving waves and

(c) the change due to the tangentially propagating part of the internally generated arriving waves

At the beginning of the first time step the specified (datum or free field) velocity, (a), is applied to the nodes on the island boundaries and the new stresses are computed in the elements (see Figure 3-2a, b). The resulting tractions are compared to the specified free-field or datum tractions, and the difference is used to determine the characteristics of the internally generated waves arriving normally, (b), and tangentially, (c), at the boundaries.

The normally propagating part of the scattered signal is found by using the Hadamard identity for outgoing waves,

$$\frac{\partial}{\partial n} \equiv -\frac{1}{S}\frac{\partial}{\partial t} \tag{3.1}$$

thus replacing the normal component of the gradient operator by a time derivative. Here S is the (unknown) wave phase velocity normal to the boundary, as shown in Figure 3-2c, and n is the local coordinate measured in the direction normal to the boundary.

Let us define the differential traction, **b** as the difference between the boundary traction vectors in the computational island and the corresponding vectors in the datum/free-field. We can apply the wave relation to obtain

$$\frac{\partial \mathbf{b}}{\partial n} = -\frac{1}{S}\frac{\partial \mathbf{b}}{\partial t} \tag{3.2}$$

so that the equation of motion gives for the contribution (b), $\Delta \mathbf{v}$, to the change in nodal velocity,

$$\frac{\Delta \mathbf{v}}{\Delta t} = \frac{1}{\rho}\frac{\Delta \mathbf{b}}{\Delta n} = -\frac{1}{\rho S}\frac{\Delta \mathbf{b}}{\Delta t} \tag{3.3}$$

(In general the vector $\Delta \mathbf{v}$ includes both longitudinal and transverse components of signals propagating normally outward through the boundary). We can also write

$$\frac{\Delta \mathbf{v}}{\Delta n} = -\frac{1}{S}\frac{\Delta \mathbf{v}}{\Delta t} \tag{3.4}$$

Combining these relationships (and eliminating S) gives

$$(\Delta \mathbf{v})^2 = \frac{1}{\rho}(\Delta \mathbf{b})\cdot\left(\frac{\Delta \mathbf{v}}{\Delta n}\right)\Delta t \tag{3.5}$$

In the usual finite element procedure the right side of equation (3.5) is known, and the normal wave contribution (b) can be found. Note that no assumptions are required regarding the material constitutive properties or the global island geometry.

In order to find the tangentially propagating portion of the scattered signal, (c) above, the non-traction stresses are used to calculate the partial nodal forces at each boundary node. When all the nodal forces are assembled in the usual finite element manner, the remaining nodal forces combine (through the nodal equations of motion) to produce the tangential contribution at the boundary nodes, Figure 3-2d. Both corrections are then added to the change in the specified velocity to provide the velocity boundary condition to be applied for the next time step. The cycle is then repeated for each time step.

This boundary velocity decomposition procedure implicitly takes account of all aspects of the problem. In particular, material nonlinearities, arbitrary angle of incidence,

boundary curvature effects and material history dependence are all naturally handled by means of the finite element discretization based on information available within the island.

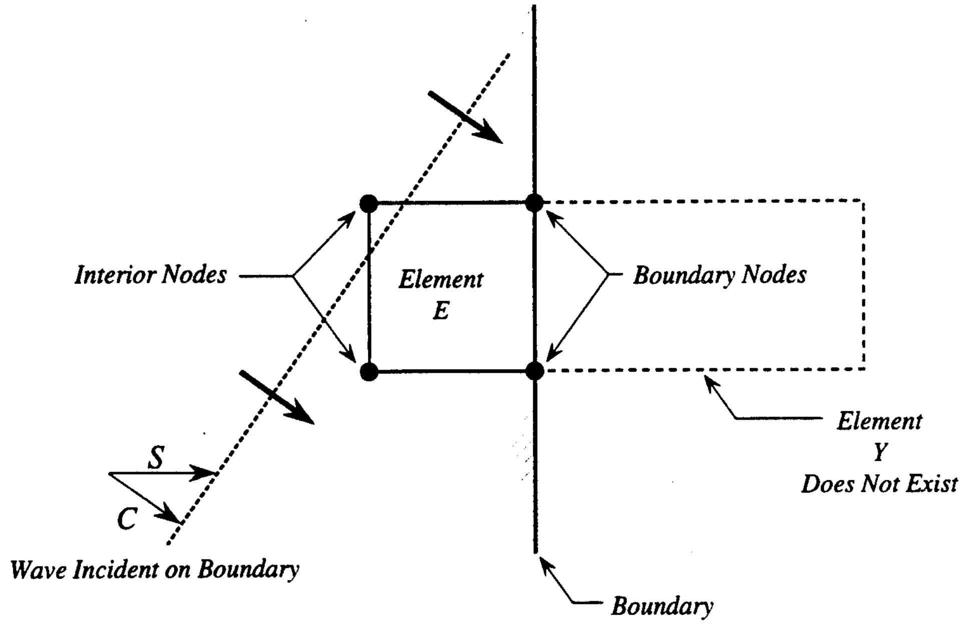


Figure 3-1. Arrival of a wave at the boundary of a finite elemenbt grid.

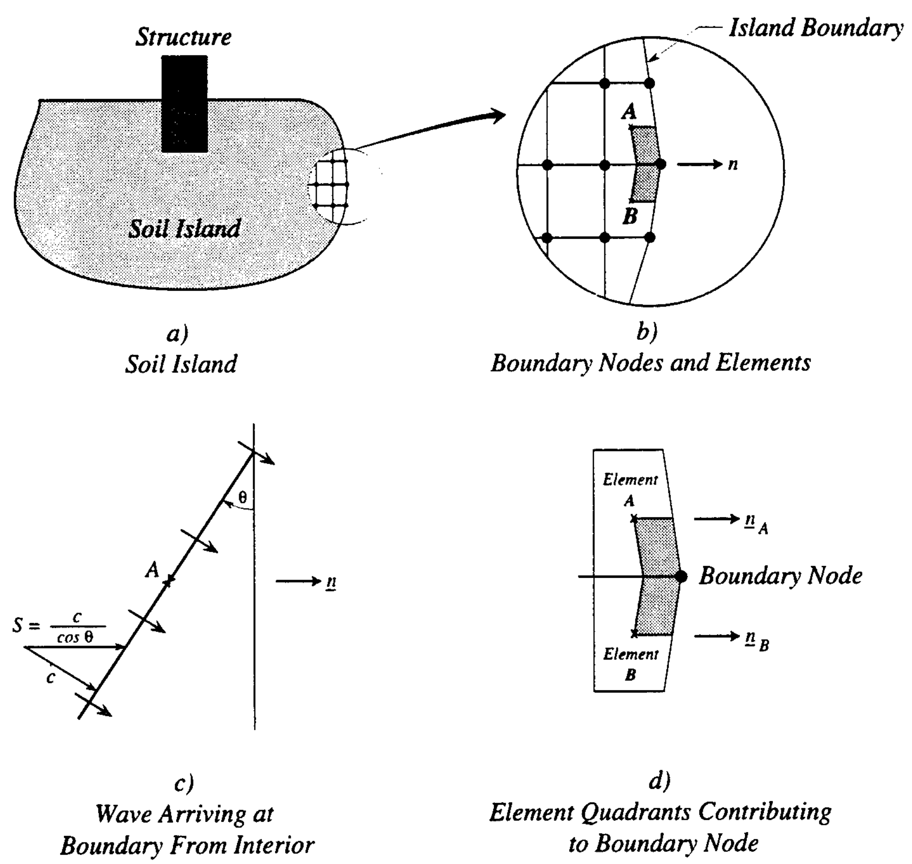


Figure 3-2. Soil Island Boundary Treatment For Transmitting Scattered Waves.

SECTION 4

SOME EXAMPLES

We have implemented simplified versions of the new procedure in several codes. These include FUSE (which deals with free-field water shock, [12]), the general purpose finite element codes EPSA and FLEX, and a number of other special purpose codes such as piezo-electric and electromagnetic wave solvers developed by Weidlinger Associates. All give extremely encouraging results, as the examples below illustrate.

The first example of the effectiveness of the new transmitting boundary procedure is shown in Figure 4-1. This figure shows the results from an axisymmetric FUSE computation of water shock arising from a shallow underwater explosion (including the effects of cavitation and nonlinear water equation of state). The top plane in each of the frames represents the water surface, but the right side (cylindrical surface) and lower plane are transmitting boundaries utilizing the new procedure. It is clear from the lower pair of snapshots that both the primary wave and its surface reflection (which causes cavitation) are well transmitted through the side and bottom of the grid with very little reflected noise.

Another example - this one linear - is shown in Figure 4-2. This figure shows the results of an electromagnetic wave calculation in two dimensions. (This is mathematically equivalent to the mechanical case of elastic S-H wave propagation from a line source with the direction of motion normal to the plane of the figure). The source consists of an electric field transient applied over the small region indicated by the square box. Note that the outward traveling waves strike the upper and lower boundaries at angles varying from normal incidence to almost grazing incidence. It is evident from the figure that the boundary treatment is very nearly "non-reflecting", as required for the scattered waves in the SMI problem. (It should be noted that the color scale is not the same for each frame of the figure, so that the late-time residual "noise", after passage of the wave front, shown in the lower right frame, is actually quite small in spite of the complicated pattern appearing in that frame).

In order to assess the new boundary treatment quantitatively, four different calculations were performed for the problem of Figure 4-2. The results obtained at the

time of the lower-left “snapshot” of that figure are shown in Figure 4-3. The four calculations are:

a) the “exact" solution - The computational grid was extended far enough so that no boundary signal could be reflected back for the space and time region of interest,

b) a “normal incidence” boundary - This calculation used the “standard" Lysmer-Kuhlemeyer type of boundary treatment,

c) a “4th Order Paraxial” boundary - This computation used a published treatment, [13] which is valid only for linear problems and is generally considered to be highly accurate, and

d) the new method - These results were shown at the lower left in Figure 4-2.

It can be seen from Figure 4-3 that the new method is as good (free of boundary reflections) as the high order paraxial scheme, although it is not perfect (compared to the “exact" solution). It is significantly better than the standard normal-incidence scheme.

Two other examples of the boundary treatment in FLEX-based codes are shown in Figures 4-4 and 4-5. The former shows results for a medical piezo-electric transducer, while the latter displays the electromagnetic field around a chrome photomask. Both figures show the efficacy of the boundary treatment.

A final example of the new procedure is given in Figure 4-6, which shows the results of one of a series of SMI analysis of tests conducted on the response of submerged target plates to hydrodynamic shock, [14]. The code used for these calculations was EPSA (Elastic Plastic Shell Analysis). The time history plots show typical comparisons of the computed motion at the center of the plate to that measured in one of the tests. Once again, the validity of the procedure is apparent.

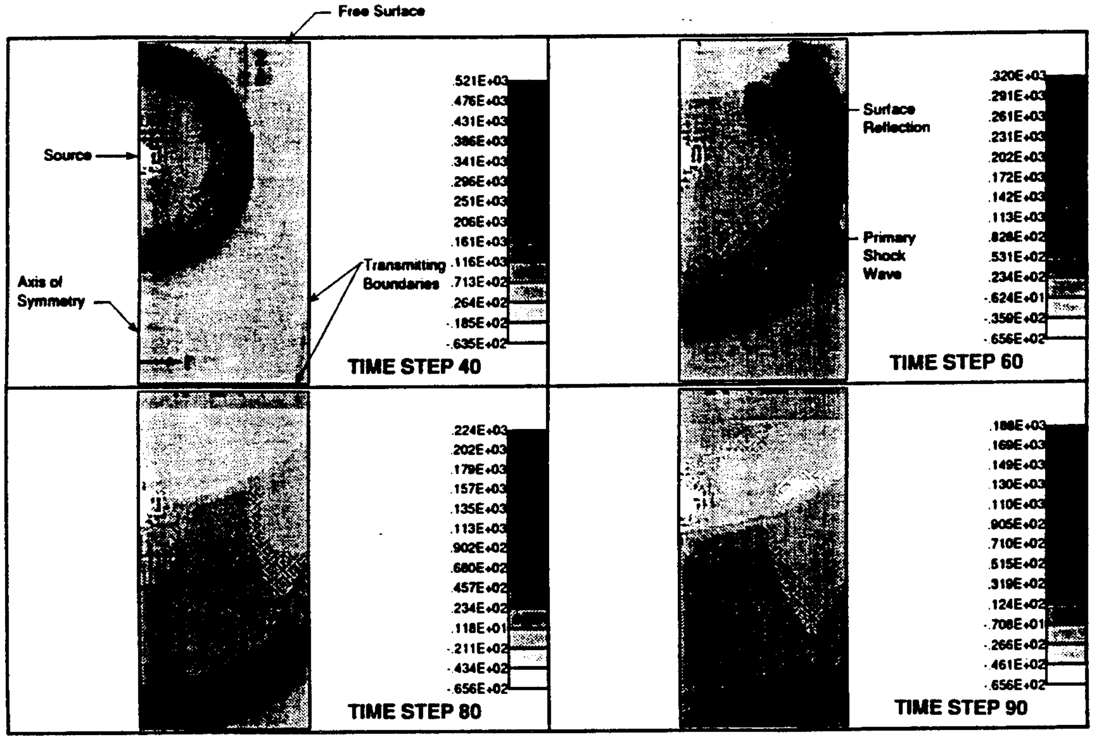


Figure 4-1. FUSE calculation showing the pressure field at four different times resulting from a shallow underwater burst. The primary shock wave and its surface reflection are transmitted out of the grid with minimal reflections from side and bottom.

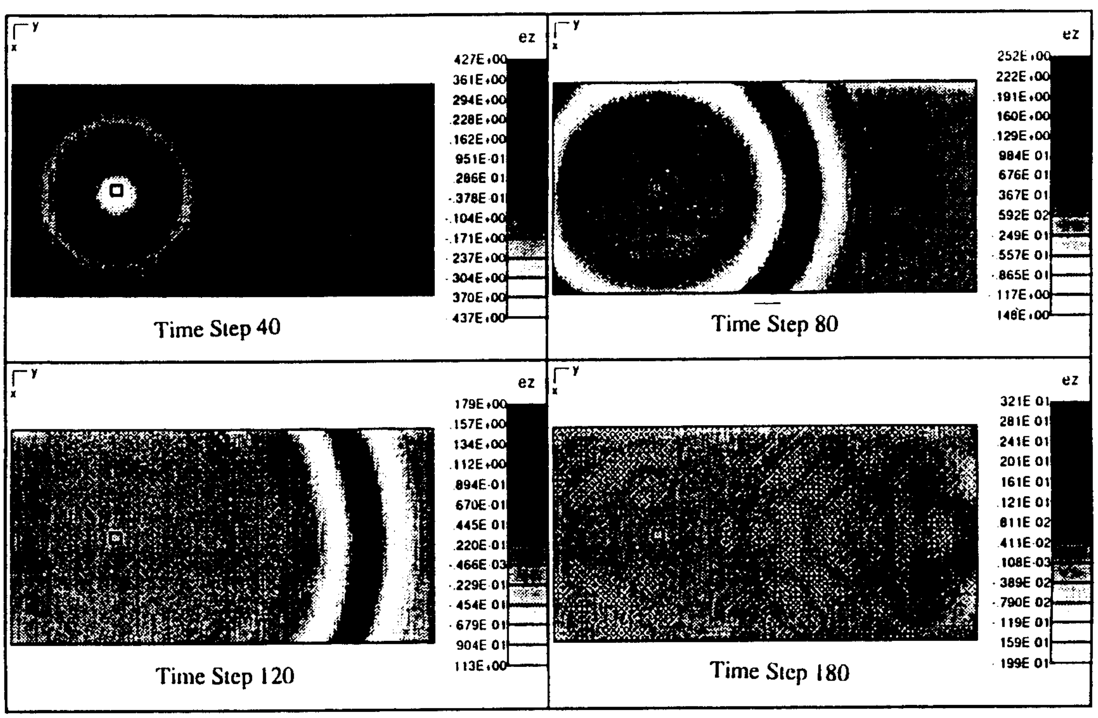


Figure 4-2. An example showing the effectiveness of the boundary absorber. A z-polarized electric field transient is applied in the small box and radiates outward with minimal boundary reflections.

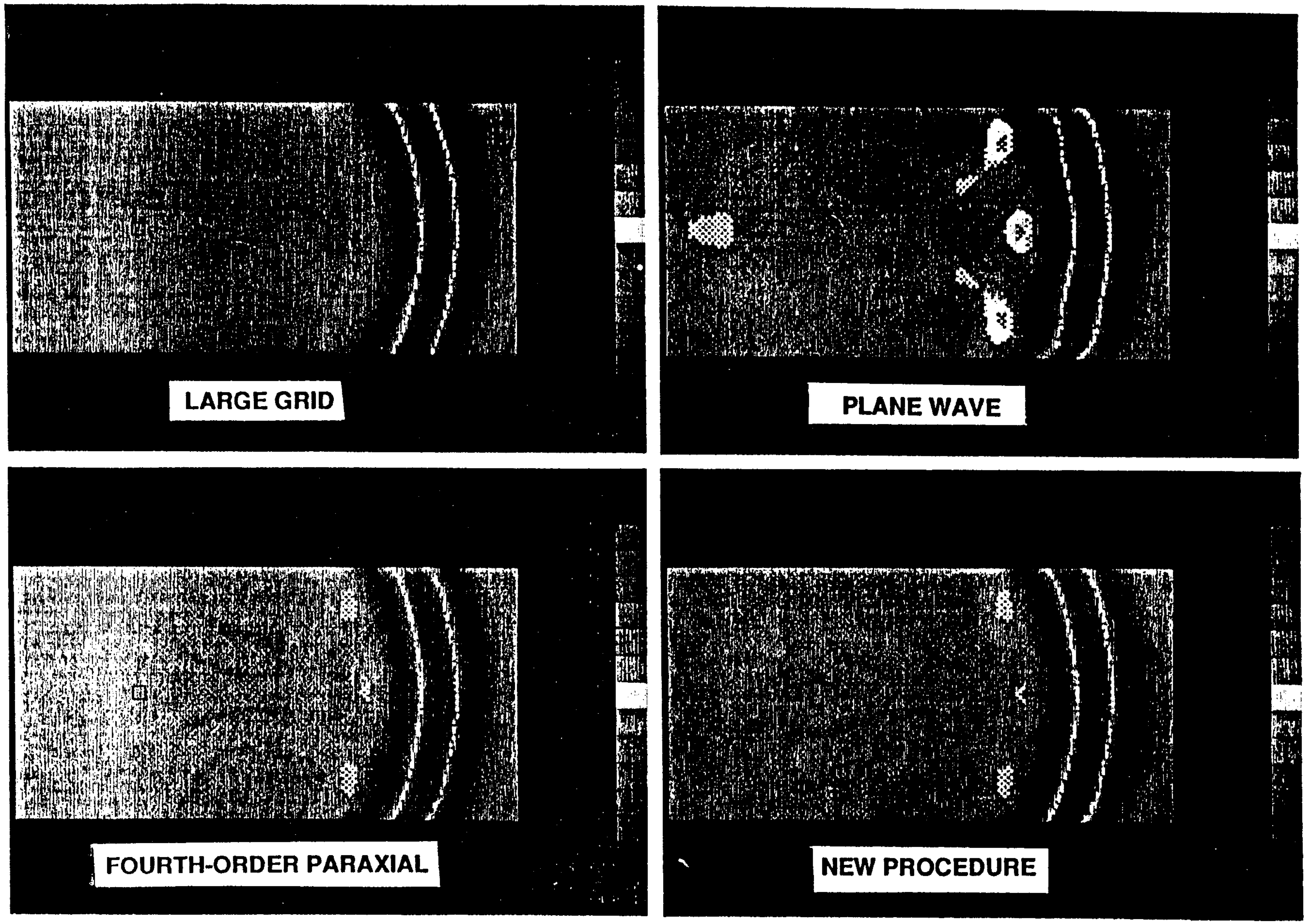


Figure 4-3. Demonstration of transmitting boundary, s-h waves generated by a line source in an infinite elastic medium. Four different FLEX calculations using: Large Grid (upper left), Plane Wave (upper right), Fourth-Order Paraxial (lower left) and the New Procedure (lower right).

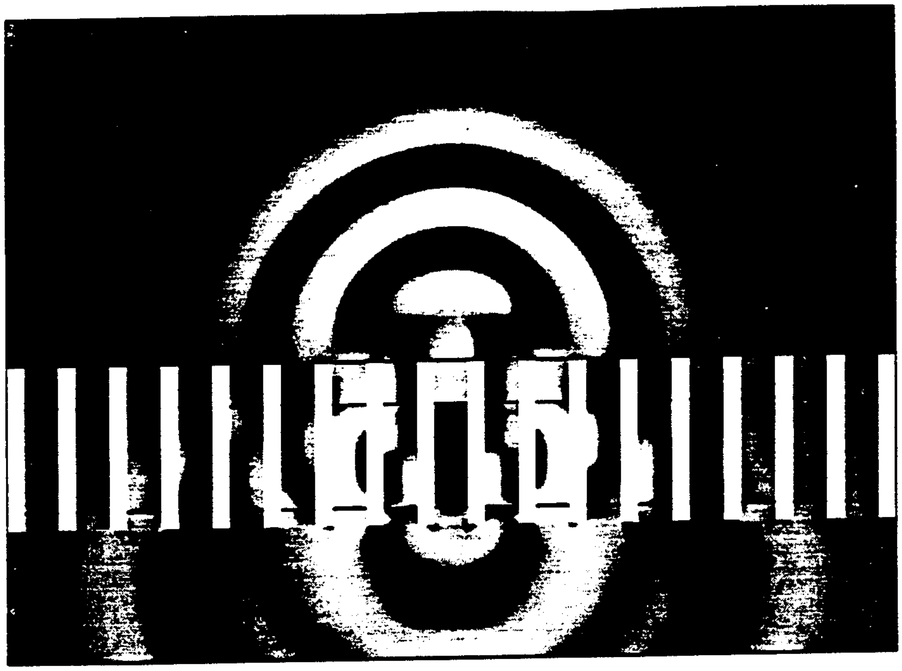


Figure 4-4. Pressure snapshot of a diagnostic medical ultrasound transducer array. The center PZT-5H ceramic element is driven by a smooth 100 nsec pulse in voltage applied to the electrodes. This PZFLEX model has transmitting boundaries on all four sides.

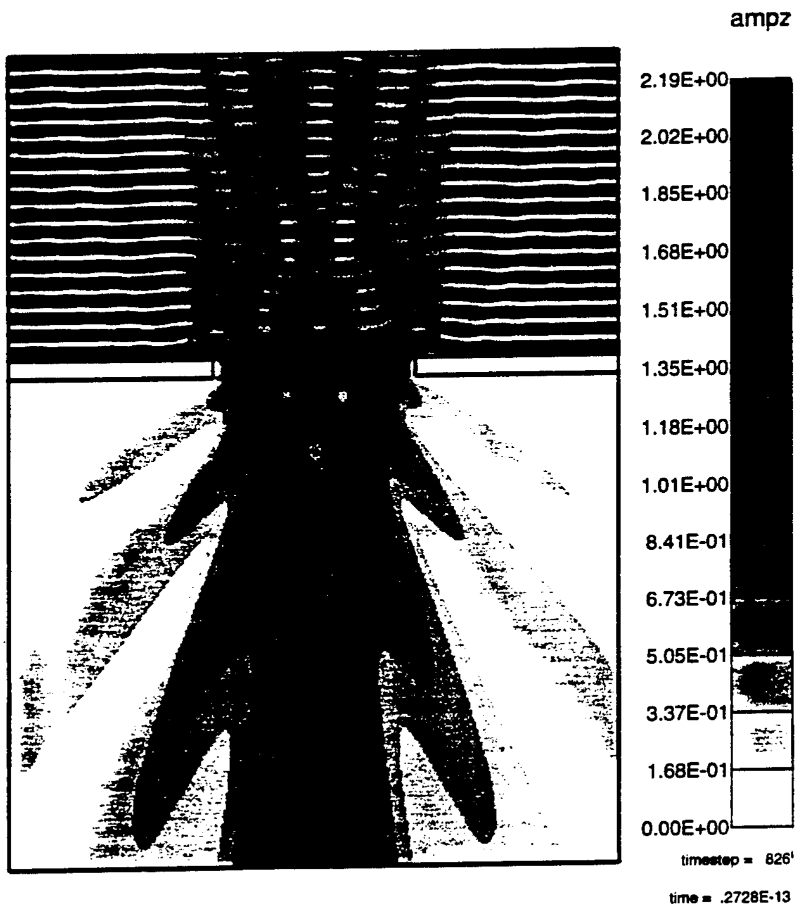
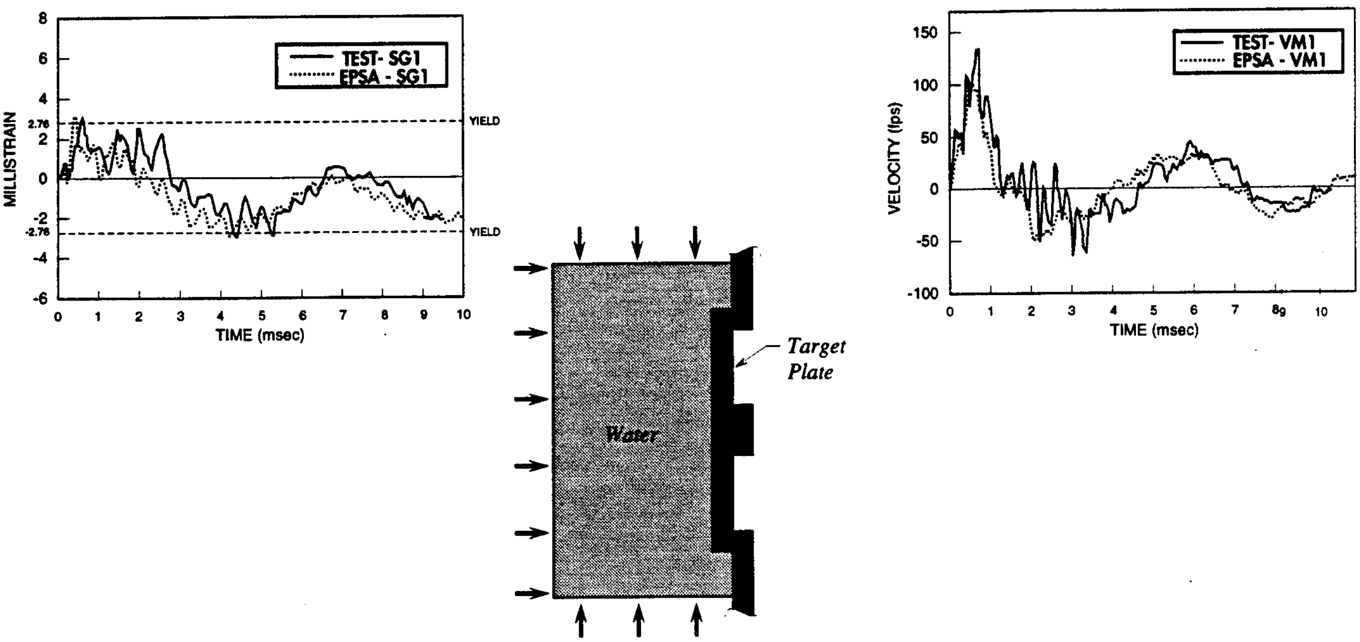


Figure 4-5. Electric field amplitude around an opening in a chrome photomask. Illumination (SMI) boundaries were used on all four sides.



Shock is Applied at Boundary of Hexahedral Mesh and Propogates through Water to Target Plate

Figure 4-6. Structure-Medium Interaction (SMI): bare plate.

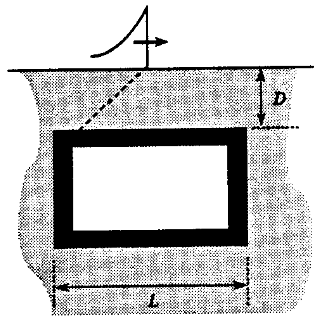
SECTION 5

ADDITIONAL CONSIDERATIONS

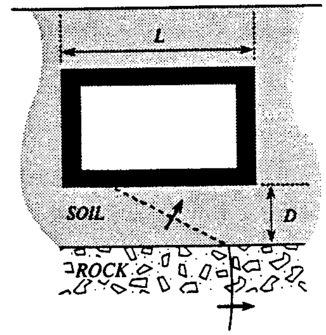
Most interaction analyses use the free field solution as the datum problem. However, there are situations in which this is not appropriate. Two examples are illustrated in Figure 5-1. A box structure, Figure 5-1a, is placed at a depth D which is small relative to the span L. A wave will hit the roof of the structure, reflect upward to surface, and bounce back as a tensile wave. Multiple reflections are possible. In Figure 5-1b, the structure is deeply buried in soil, but close to a very stiff layer below it. A head wave attached to an outrunning ground shock signal reaches the floor of the structure. Again, multiple reflections are possible. In both cases (and others), the free field signal would not contain the real reflections from the real interfaces caused by the presence of the structure. Applying free field velocities, tractions, or a combination to the edge of the structure, or to an artificial boundary a short distance away, would miss part of the real signal.

For situations such as those suggested by Figure 5-1, it may be most appropriate to solve the problem twice, first with a coarse model, and then at the desired level of refinement. The results of the coarse solution are used as the datum to drive the refined soil island.

A further consideration in SMI analysis involves the issue of possible constitutive incompatibility between the datum problem and structural analysis. One method for evaluating the consequences of any difference in the material models used for the free field and soil island calculations is to calculate a "free-field island", i.e., one without a structure. By comparing the results of such a calculation to the free-field characterization, one may confirm that no significant spurious signals are produced by potential constitutive or numerical modeling incompatibilities between the two calculations.



Shallow Buried Structure



Deep Stiff Layer

Figure 5-1. Examples for which the free field solution is a poor choice of datum problem.

SECTION 6

SUMMARY AND CONCLUSIONS

An improved SMI procedure has been developed which is completely general with respect to the constitutive behavior of the field medium. Application of the procedure in a number of different cases indicates that it is highly effective and computationally efficient. The new scheme is aimed at the full spectrum of structure-medium interaction technology of interest to the Defense Nuclear Agency.

The new method permits the conditions at the computational boundaries to deviate from the corresponding free-field conditions in a manner completely consistent with the constitutive, geometric and discretization differences between what is inside the computational island and what is in the free field. The interior characteristics of the island determine the effect on the conditions at the island boundary of the presence of the structure or any other material not present in the free-field. In principle, the method could even be used with empirically based free field information (although sufficient data for this purpose are not usually available). The method utilizes both the traction and velocity of the free field as a datum or basis from which the actual boundary values are obtained as a result of waves impinging on the boundary from within.

The procedure minimizes the consequences of any incompatibilities between the free field information and the SMI model. The treatment is valid for late times, nonlinear material behavior and complicated geometries, including cases in which the driving source is contained outside as well as inside the computational boundaries.

Finally, the method is compatible with most of the commonly available finite element codes.

SECTION 7

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